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Factors affecting rates of ice cutting with a chain saw

Barry A. Coutermarsh

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

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Military winter bridging procedures with an ice cover present on the waterway may involve cutting the ice away with chain saws to provide an ice-free crossing zone. This report investigates the cutting rates possible from one type of chain saw with two chain configurations, two operators, three cut lengths and three ice thicknesses. A statistical analysis is used to determine the effect the various factors have upon cutting rate and suggestions are made for chain modifications that might further improve cutting performance.

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PREFACE

This report was prepared by Barry A. Coutermarsh, Research Civil Engineer, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by DA Project 4A762784AT42, *Cold Regions Engineering Technology;* Task 5.0, *Vehicle/Terrain Interaction;* Work Unit CS/001, *Winter River Mechanics.*

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASURE

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*by*	*To obtain*
inch	25.4	millimeter
foot	0.3048	meter
foot/minute	0.0000846666	meter/second

Factors Affecting Rates of Ice Cutting With a Chain Saw

BARRY A. COUTERMARSH

INTRODUCTION

The U.S. Army Ribbon Bridge has been successfully deployed in the winter both on the ice and in a channel cut with chain saws (Mellor 1988). A bridging commander, however, will need to know the time involved with each of these procedures to effectively plan an operation. This report describes an initial study undertaken to determine chain saw cutting rates in ice and presents a preliminary empirical equation that can be used to predict cutting rate, given ice thickness and a defined chain type.

A Ribbon Bridge deployment will be most seriously hindered by an ice cover of over 6 in. It appears that ice thinner than this can be broken up and pushed out of the way by a Bridge Erection Boat (Stubstad et al. 1984). This was taken as our lower thickness boundary.

The thickest ice to be cut depends on the anticipated traffic load. There are guidelines available on the thickness of ice necessary to support a load when the ice itself is used as the bridge (Coutermarsh 1987). However, since it is possible to deploy the bridge on top of an ice sheet, it might be possible to use the bridge as a load spreading base for traffic heavier than what the ice alone could accommodate. A thickness sufficient to hold the bridge and the anticipated traffic load needs to be investigated. For this technique to be useful, that thickness would need to be less than the thickness necessary to carry the anticipated load without any load spreading. This would also define the maximum ice thickness that would have to be cut. This limit is not yet determined, but for our purposes the upper limit of ice cut was 25 in. A Ribbon Bridge was deployed on 25-in.-thick ice to demonstrate the feasibility of this procedure.

A skip-tooth chain and a modified skip-tooth chain were used to study the effect of chain design on ice cutting rates, while at the same time the effects of cut length and saw operator on the cutting rate were investigated. The problem was analyzed statistically because of the nature of the pertinent variables.

In addition, a chain was analyzed to determine modifications that might increase cutting rates over those obtained in this study. Further tests will concentrate on finding a more aggressive tooth design, and one that is more efficient at removing cuttings to prevent chain clogging.

EQUIPMENT

The saw used in the study was a Homelite model 550 with a 24-in. bar. The Homelite saw, according to the manufacturer, has an engine speed of 6000–12,000 rpm (Homelite 1979). This would give an approximate chain cutting speed of 2800 ft/min.

The chains used in the study were skip-tooth designs with a tooth spacing of 2.25 in. One was modified by filing off approximately 1/16 in. from the gauge, resulting in a cutting depth of about 2/16 in. (Fig. 1). This allowed the tooth to cut deeper and to chip the ice rather than shaving it. The remaining chain was left in its original condition with a cutting depth of about 1/16 in. The chains were sharpened in the normal way, i.e., by filing the gullet (Fig. 1) before each test block.

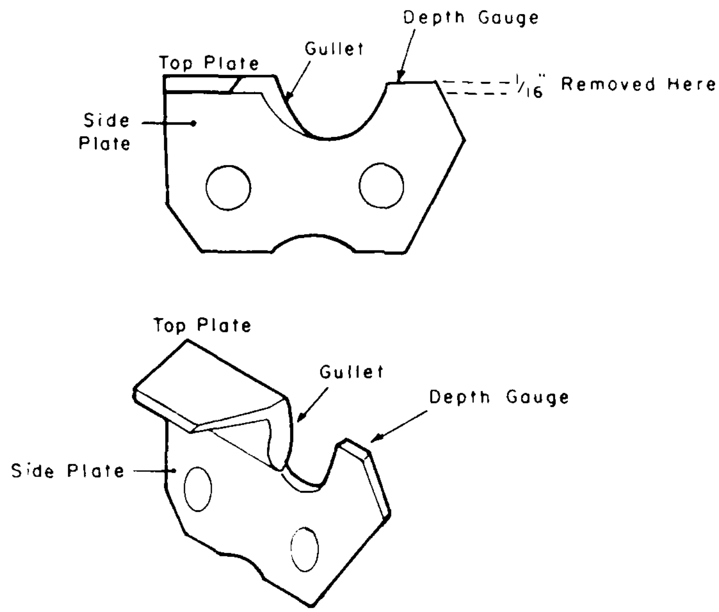


Figure 1. Chain saw cutter detail.

THEORY

A chain saw is classified as a continuous belt cutting machine (Mellor 1976). The cutting speed of the saw through the material is related to the tool chipping depth and cutting speed, the angle the saw makes with the free surface of the material, the production and conveyance of the cuttings, as well as the power available to the saw, and the force the saw exerts on the material being cut. The dynamics and kinematics of cutting with this type of saw can become somewhat complex and it is beyond the scope of this paper to detail how a saw cuts. A good treatment of the subject has been provided by Mellor (1976, 1977, 1978)

A chain saw, by its very nature of operation, is difficult to analyze from a rigid theoretical point of view. Its cutting angle is changing almost constantly as the operator makes subtle adjustments to improve cutting speed efficiency or comfort. The force the operator applies through the saw bar to the material is changing in response to these adjustments, operator fatigue or any number of reasons in effect at the time of cutting. The cutting speed can vary in response to the chain becoming pinched by the material, to throttle manipulations, to cut angle adjustments by the operator or to chain interaction with water beneath the ice.

The variability in cutting styles means that a chain saw's performance may vary substantially from what a theoretical analysis might suggest. It also means that to obtain a good indication of chain saw cutting rate we must consider a statistical analysis that will span the range of expected performances. This study is a first step in that direction.

PROCEDURE

A two-level factorial design strategy with a center point was used to plan the cutting study, as it offers maximum flexibility in the early stages of the experiment and initially produces a good deal of definable information about the variables involved. The variables chosen were chain design, operator and cut length, with ice thickness as a block variable. This resulted in a 2^4 factorial design with two qualitative variables—operator and chain type—and two quantitative variables—cut length and ice thickness. A center point for the quantitative variables was planned to define any nonlinearity in the model and, as the results will show, it was needed. As it turned out, this center point was not a true center point in the classic statistical sense, as will be explained later. Adding a center point results in 17 runs for one full factorial if there are no replications.

There are physical limitations to obtaining the necessary ice thicknesses; we had to wait for the ice to build to the required thickness instead of having all three required ice thicknesses at once as we would have had in a laboratory. This required that the experiment be set up in at least three blocks, creating the disadvantage of confounding the four-factor interactions with the block effect. But, since higher order interactions are usually negligible, this was an acceptable design decision.

The ranges of the variables, where possible, were chosen to coincide with the physical region of interest as defined in the *Introduction*. The operator variable is impossible to handle in this manner because of the infinite possibilities of operator type. It was included in the study at first to allow us to obtain some idea of its effect. Its interpretation will be discussed in more detail in the following sections.

The cut length variable ranged between 5 and 15 ft. These lengths were chosen to bracket an approximate ice chunk size that could be handled easily during removal. Cuts were continuous throughout the length.

Three ice thicknesses were chosen to correspond to the lower, upper and center of the range between 6 and 25 in. The theoretical center point would then be 15.5 in. Because of the rapid arrival of extremely cold weather at the start of the study, the available lower ice thickness was 7 in. When the study was started the upper limit was unknown, which meant that the center point would be estimated before the full range was known. When temperatures started to moderate in the initial study area in New Hampshire, an ice thickness of 11 in. was used for the center point. The final ice thickness was obtained at a bridging exercise at Fort McCoy, Wisconsin, and turned out to be 25 in. The ideal center point of the design should therefore be at 16 in. but it will be seen that 11 in. is still sufficient to define nonlinearity in the model.

The chain designs and modifications were chosen as a result of work done at CRREL that determined what constituted a good ice cutting chain. Future tests will incorporate more chain modifications to allow us to get a feel for the relative merits of each modification.

Cutting rate was determined by making straight line cuts with the blade completely through to the water. This meant that in the 7- and 11-in. thick ice, water was thrown up by the saw.

Three series of cuts were made in the 7-in. ice, four in the 11-in. ice and four in the 25-in. ice for a total of 48 cuts.

RESULTS

The experiments proceeded in three design blocks based upon ice thickness. The variables were coded as for factorial designs, with the lower level as -1, the center point as 0 and the upper level as +1. The runs were randomized and three replicates were performed.

Block 1: 7-in.-thick ice

Table 1 lists the results for 7-in.-thick ice.

An Analysis of Variance (ANOVA) study (Table 2) showed chain type as having the greatest effect upon cutting rate, it being significant at the 0.01 level. The remaining single effects of cut length and operator, as well as all of the two factor interactions, were not significant at the 0.1 level. It should be remembered that the significance level is an indication of the possibility of

Table 1. Chain saw cutting rate data and experimental parameters for 7-in.-thick ice.

Run order	*Operator*	*Chain type**	*Cut length (ft)*	*Time (s)*	*Cutting rate (ft/min)*
1	BC	mod	15	50	18.00
2	JS	mod	15	52	17.30
3	BC	reg	5	15	20.00
4	JS	reg	5	15	20.00
5	BC	reg	5	15	20.00
6	BC	reg	15	51	17.64
7	BC	mod	5	9	33.33
8	JS	mod	5	7	42.85
9	JS	mod	5	6	50.00
10	JS	mod	15	19	47.36
11	JS	reg	5	13	23.07
12	JS	reg	15	41	21.95
13	BC	reg	15	41	21.95
14	JS	reg	5	13	23.07
15	BC	mod	5	7	42.85
16	BC	mod	15	19	47.36
17	JS	mod	5	7	42.85
18	BC	mod	15	18	50.00
19	BC	reg	15	37	24.32
20	JS	reg	15	37	24.32
21	JS	reg	15	41	21.95
22	BC	reg	5	13	23.07
23	JS	mod	15	23	39.13
24	BC	mod	5	7	42.85

* Mod - modified chain

Table 2. Variable effects and significance for 7-in.-thick ice.

Sources of variation	*Effect*	*df*	*Mean square*	*F-ratio*	*Significance*
Main effects					
Chain type	17.7	1	1882.2	24.9	*Sig at 0.01
Cut length	−2.7	1	44.4	0.6	NS
Operator	1.0	1	6.5	0.1	NS
Two factor interactions					
Chain type by cut length	−3.2	1	61.8	0.8	NS
Chain type by operator	−0.2	1	0.2	0.0	NS
Cut length by operator	−2.3	1	30.4	0.4	NS
Residual		17	75.5		

* $F_{0.99}(1,17) = 8.40$
$F_{0.95}(1,17) = 4.45$
$F_{0.90}(1,17) = 3.03$

the measured response happening by pure coincidence as opposed to being the result of the variable or interaction indicated. A low significance level value tells us that a random occurrence is not very likely to be the cause of the measured response and therefore the indicated variable must be responsible for it. It follows that as the significance level value increases, the response is more and more likely to have been caused by a random occurrence and therefore not much effect can be attributed to the associated variables. In this study a significance level of 0.1 was the highest that we would accept for judging the importance of a variable or interaction. Anything above this was judged not significant.

An ANOVA assumes the data are independently and identically distributed in a normal distribution (Box et al. 1978). This assumption may not be tenable, although making random test runs will usually validate the assumption.

It is interesting to point out the presence of two points that appear to be outliers. In Table 1 the first two runs appear to have a cutting rate more appropriate to the unmodified chain than the modified chain for which they are listed. Figure 2 is a graph of the data with the two suspected outliers below the other values for the modified chain cutting rates. It is possible that the chain type was incorrectly listed for these two cuts. These were also the first two cuts of the day and a cold or tight chain could have caused high tangential friction in the chain, which would require greater tractive thrust for similar cutting rates.

It can be seen from the above ANOVA there is a significant difference between chains, while cut lengths and operators show little difference. These conclusions are presented in Figure 3, which is a plot of cutting rate against cut length and operator. It is evident that the modified chain outperforms the unmodified chain in all but two instances for the 15-ft cuts. These two points are the suspected outliers. It can also be seen that there is little difference in cutting rate between operators or cut length, except for the suspected outliers.

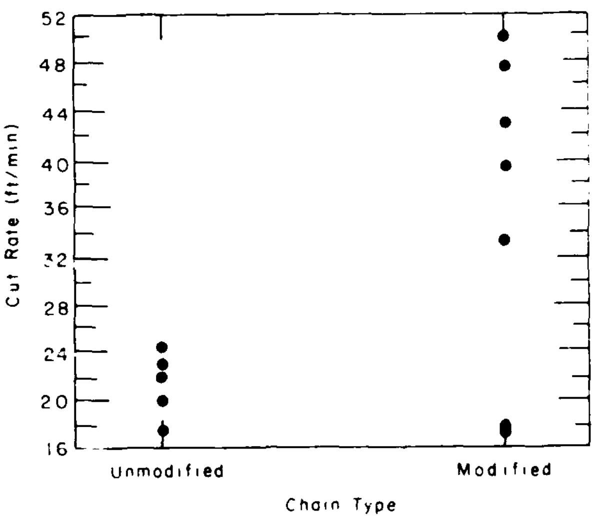


Figure 2. Chain type versus cutting rate for 7-in. ice. Two outliers are evident in the lower right.

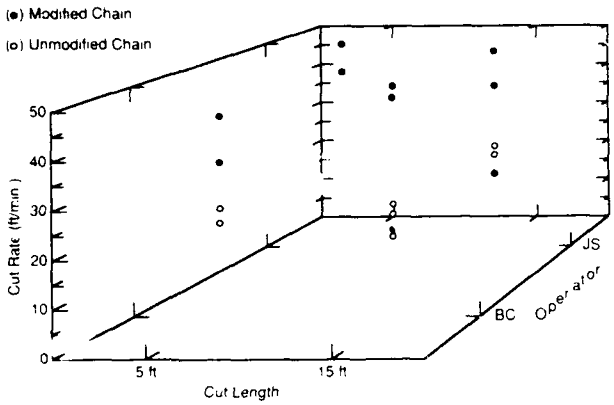


Figure 3. Ice cutting rate (in 7-in. ice) versus cut length and operator. The two outliers are the lower modified chain points at the 15-ft cut length with one for each operator.

We assumed before the study that ice thickness would be highly significant, but this does not show up in the first block since no variation had taken place at this point.

Block 2: 11-in.-thick ice

The next block of data taken was to be the center point, at an ice thickness of 11 in. and a mid-point cut length of 10 ft. The qualitative variables, chain type and operator, were run at both of their levels. Table 3 lists the data gathered at this thickness.

An ANOVA of the 11-in.-thick ice data examined the relationship between the operator and chain variables. Cut length was 10 ft only in the 11-in. ice thickness, which makes it impossible to determine its effect in this thickness. Table 4 shows that the most significant effect is, again, from the chain type, with the operator effect not significant at the 0.1 level.

Figure 4 is a plot of the data from both blocks; it shows the decrease in cutting rate associated with the increase in ice thickness. Chain type has the most significant effect upon cutting rate, with the modified chain generally outperforming the unmodifed chain, as expected. The exceptions are the two suspected outliers at the 7-in. thickness and one point by operator BC at the 11-in. thickness.

Table 3. Chain saw cutting rate data and experimental parameters for 11-in.-thick ice.

Run order	*Operator*	*Chain type**	*Cut length (ft)*	*Time (s)*	*Cutting rate (ft/min)*
1	BC	reg	10	47	12.76
2	JS	reg	10	68	8.82
3	JS	reg	10	66	9.09
4	BC	reg	10	37	16.21
5	BC	mod	10	33	18.18
6	BC	mod	10	28	21.42
7	JS	reg	10	32	18.75
8	BC	reg	10	33	18.18
9	JS	mod	10	24	25.00
10	BC	mod	10	19	31.57
11	JS	mod	10	21	28.57
12	BC	mod	10	22	27.27
13	JS	mod	10	24	25.00
14	JS	mod	10	22	27.27
15	BC	reg	10	30	19.99
16	JS	reg	10	41	14.63

* Mod - modified chain

Table 4. Variable effects and significance for 11-in.-thick ice.

Sources of variation	*Effect*	*df*	*Mean square*	*F-ratio*	*Significance*
Main effects					
Chain type	10.7	1	460.6	25.9	*Sig at 0.01
Operator	−1.1	1	4.5	0.3	NS
Two factor interactions					
Chain type by operator	−0.2	1	0.2	0.0	NS
Residual		12	17.8		

* $F_{0.01}(1,12) = 9.33$
$F_{0.05}(1,12) = 4.75$
$F_{0.10}(1,12) = 3.18$

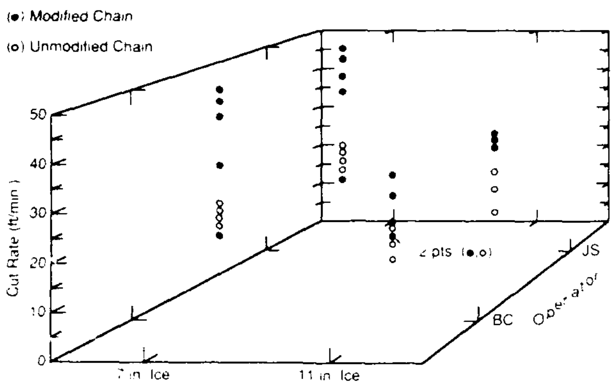


Figure 4. Combined 7- and 11-in. ice cutting rate versus ice thickness and operator. The outliers appear as the lower modified chain points for the 7-in. thick ice.

Table 5. Modified and unmodified chain comparison for the 11-in.-thick ice with a 95% confidence interval for the difference between the means.

Sample statistics	*Regular chain*	*Modified chain*	*Pooled*
No. of observations	8	8	16
Average	14.8038	25.535	20.1694
Variance	18.358	17.6078	17.9829
Std. deviation	4.28462	4.19616	4.24062
Median	15.42	26.135	19.37

Difference between means = −10.7312
Conf. interval for diff. in means: 95%

A two-sample analysis (Table 5) between the chains found that the modified chain has an average cut rate that is 73% higher than the unmodified chain.

Block 3: 25-in.-thick ice

In the last block the chain types were not varied nor was the operator (the second operator was not available for the third block). We decided to use the fastest chain type to obtain the highest estimate of cutting rate. We could not ascertain operator effect over the entire data set, but it can be seen from the previous blocks that the operator effect has not been significant, although it would have been desirable to test this on the thicker ice also.

Table 6. Chain saw cutting rate data and experimental parameters for 25-in.-thick ice.

Run order	*Operator*	*Chain type**	*Cut length (ft)*	*Time (s)*	*Cutting rate (ft/min)*
1	BC	mod	15	132	6.81
2	BC	mod	5	48	6.25
3	BC	mod	5	50	6.00
4	BC	mod	15	157	5.73
5	BC	mod	5	53	5.66
6	BC	mod	15	159	5.66
7	BC	mod	5	52	5.76
8	BC	mod	15	128	7.03

* Mod - modified chain

The cut length was varied even though it was not significant in the previous tests. We speculated that in the thick ice of the third block it might show an effect.

Table 6 presents the data for this thickness. We can use these additional points for the 25-in.-thick ice to further demonstrate the effect of ice thickness and cut length.

A one-way ANOVA was performed on the 25-in.-thick ice data to ascertain the effect of cut length (Table 7). It can be seen that its effect was not significant at the 0.1 level. It is evident that the length of the cut over the range studied had little effect upon cutting rate. Perhaps a greater cut length would start to show more influence.

CUTTING RATE PREDICTION MODEL

The data set can now be used to create a preliminary empirical model to predict cutting rate, given ice thickness and a defined chain design. The model will be based upon the data from the modified chain without distinction between cut length or operator. The final model will therefore reflect some of the variability from these factors, which will make it general in regards to its predictive capability. It should also be understood that the model is based upon ice thickness, with no attempt made to break out the factors within ice thickness that may have an effect upon the cutting rate. For example, further study may show that ice temperature or grain size may have an important effect upon cutting rate. The same point can also be made regarding the chain design. The cutting rate could vary dramatically with variations in chain design, as can be seen from the difference obtained in this study be-

Table 7. Variable effects and significance for 25-in.-thick ice.

Sources of variation	*Effect*	*df*	*Mean square*	*F-ratio*	*Significance*
Main effects					
Cut length	0.4	1	0.3	1.1	NS
Residual		6	0.29		

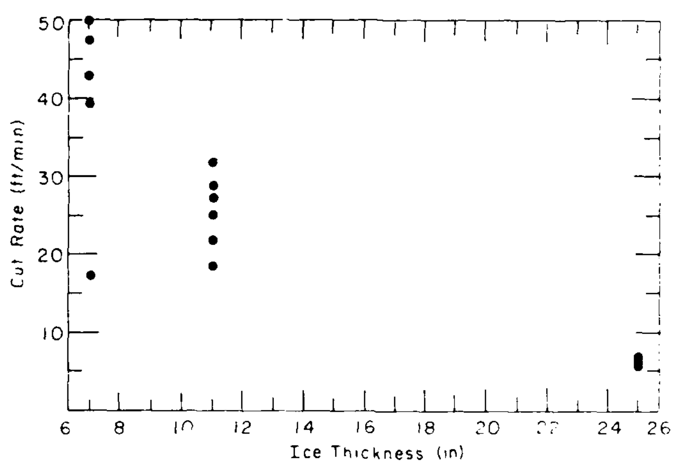


Figure 5. Plot of cutting rate versus ice thickness for the modified chain. The data include different cut lengths and operators.

tween the two chain designs. The model is developed with these factors in mind and, because of them, we made no attempt to make the variables nondimensional; therefore, the equation depends upon the metric used to measure the variables.

Figure 5 is a plot of cutting rate versus ice thickness; cutting rate decreases exponentially with increasing thickness.

The exponential regression fitted to these points gives the coefficients shown in Table 8 for the model, where ice thickness is in inches and cut rate is in feet per minute. The model explains 90.33% of the scatter as shown by the adjusted R^2 value.

The adequacy of the fit was checked by the ANOVA listed in Table 8 as well as by plotting residuals. Figure 6 shows the regression line fitted to the data points. It is evident that there is more scatter at the 7-in. ice thickness than at the other thicknesses. The most notable departure comes from the two points that were the suspected outliers.

Figure 7a is the residual plot showing the magnitude and pattern of this scatter. An inspection of the residual plots versus cut length and operator (Fig. 7b and c) shows these suspected outliers as being the most significant departures. Figure 7c indicates that the operator variable is also responsible for a lot of scatter. This is because only one operator was used for the thickest ice. The cutting rates in the thick ice were lower than in the previous ice thicknesses and only show up attributed to that one operator. Figure 7a shows more scatter for the thinner ice than for the 25-in.-thick ice. The cuts in the 7- and 11-in. ice were difficult. The saw threw a lot of water onto the ice surface, which made it extremely slippery, so the cuts were probably not as consistently made because of the traction problems. This might also manifest itself in the operator effect, depending upon how each operator handled the situation. Cut length shows no systematic pattern of residuals that would suggest an effect attributable to its influence.

Table 8. Exponential regression coefficients and ANOVA for the full regression.

Exponential model: Cutting rate = (a+b[ice thickness])
Dependent variable: Cutting rate (ft/min); independent variable: ice thickness (in.)

a. Regression coefficients.

Parameter	*Estimate*	*Standard error*	*T value*	*Probability level*
Intercept	4.33341	0.0991771	43.6936	0.00000
Slope	−0.10101	6.48143×10^{-3}	−15.5844	0.00000

b. Analysis of Variance

Source	*Sum of Squares*	*df*	*Mean square*	*F-ratio*	*Probability level*
Model	16.46460	1	16.46460	242.8750	0.00000
Error	1.762551	26	0.067790		
Total (corr.)	18.227154	27			

Correlation coefficient = 0.950421
Stnd. error of est. = 0.260366
R^2 = 90.33 %

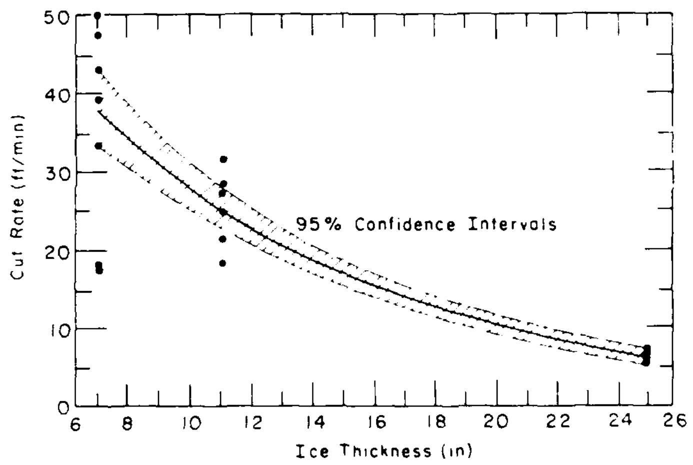


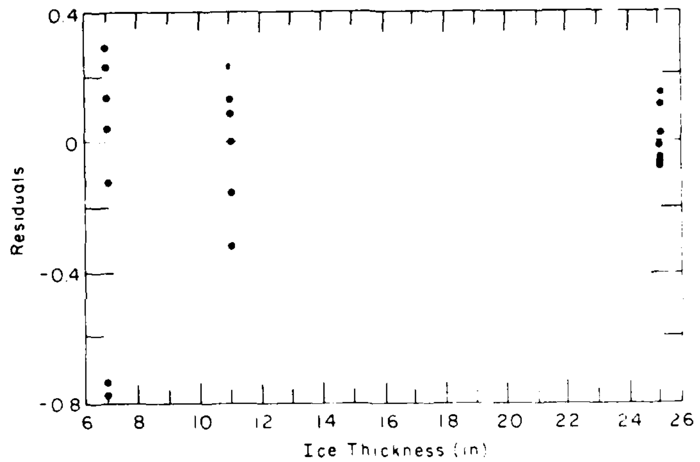
Figure 6. Cutting rate versus ice thickness with exponential regression curve and 95% confidence interval for the fit.

The final empirically derived formula is

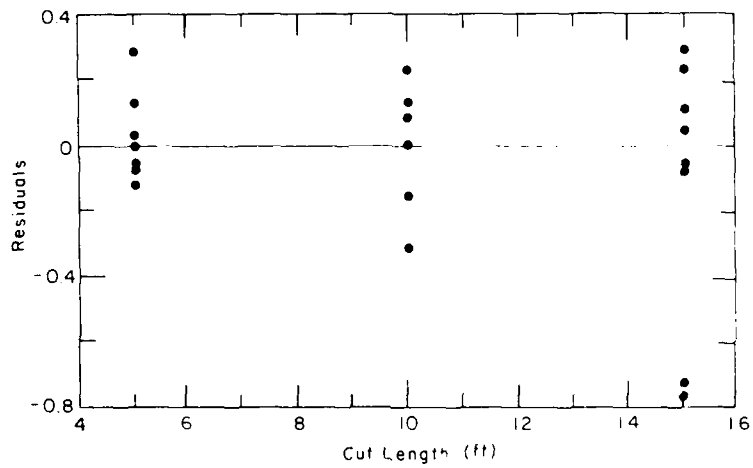
$$\text{cutting rate (ft/min)} = e^{[4.33+(-0.10 \times \text{ice thickness [in.]})]}.$$

This is a preliminary formula that should only be applied over the 7- to 25-in. range of ice thickness, with the modified chain and saw configurations close to what was used in this study. As could be seen from the above analysis, cutting rate is highly dependent upon chain configuration. Further work will concentrate on improving cutting rate and testing how robust this formula is with different variable combinations. Work should also be done to determine the effect of the different attributes of ice, as discussed before.

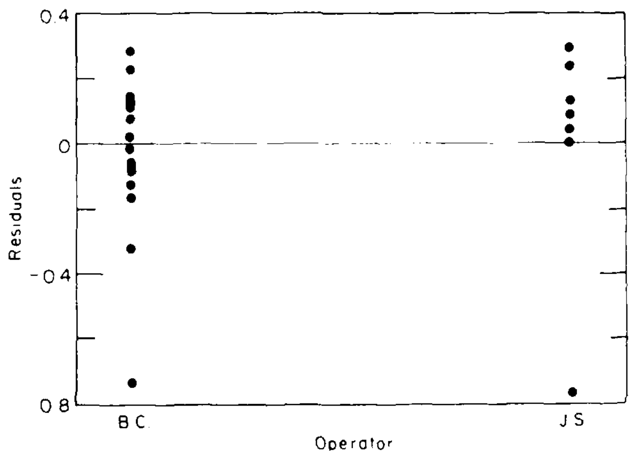
Cutting tests using the same chain saw that we used in this study were carried out in 1987 in Korea on 7- to 8.5-in.-thick ice with different operators. That study gives us only two continuous cuts for comparison; those cutting rates were 40



a. Ice thickness.



b. Cut length.



c. Operator.

Figure 7. Plots of cutting rate regression residuals versus variables.

and 47 ft/min with the gauges filed completely off the chain (Mellor and Calkins 1988). These rates compare closely with the results obtained in this study in 7-in. ice and also with predictions based on the above equations.

PERFORMANCE IMPROVEMENTS

Some general observations about the ice cutting follow.

In the 7- and 11-in. ice, where the saw cut through to the water, the saw threw a spray of water towards the operator and onto the ice surface. The operator had to stand off to the side of the cut to avoid being soaked by the spray. This meant that the saw was held away from the operator's body and was therefore not in the best position for cutting. Adding a splash guard to the saw might improve this situation.

The operator slipped around where there was water on the ice. This obviously affected performance in that the operator could not keep a steady force on the saw blade to maintain maximum saw traverse speed.

In the 25-in. ice, the saw did not cut through to the water, so traction was not a problem. The natural ice surface was rough enough to provide adequate footing. However, a large amount of ice shavings built up around the blade and seemed to interfere with the cutting. This problem was not noticed in the thinner ice, perhaps because the water flushed the shavings out or the volume of shavings produced was not enough to bind the saw.

In the thinner ice, the operator cut by holding the saw blade at approximately a 60° angle to the ice and moving the saw more or less horizontally. In the 25-in. ice it was easier to pull the saw blade up partially out of the cut and allow it to cut its way back down while also moving it horizontally through the ice. The thicker ice also required more rocking motions to work the saw through the material and to clear the shavings.

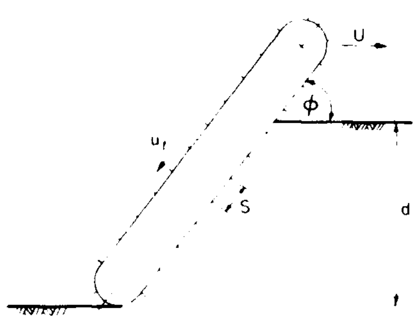


Figure 8. Chain saw blade and symbols used in the text (after Mellor 1976).

To improve performance it is helpful to look at the kinematics of cutting as detailed by Mellor (1976). Figure 8 shows the symbols to be used in the following analysis.

The chipping depth l of the saw is related to the tangential tool speed u_t, the saw traverse speed U, the spacing between teeth S, and the angle of the saw ϕ by the following formula

$$l_{max}=(U/u_t)(S)\sin\phi_{max}\,. \tag{1}$$

The maximum chipping depth will occur at ϕ=90° and eq 1 reduces to

$$l_{max}=(U/u_t)(S)\,. \tag{2}$$

At our fastest average cutting rate of 45.2 ft/min, which is used as the saw traverse speed U in eq 2, a cutter working length of 0.0625 in. (1/16 in.) and our tooth spacing S of 2.25 in., the theoretical maximum chipping depth for our saw from eq 1 is

$$[(45.2/2800)\times 2.25 \text{ in.}]=0.0363 \text{ in.} \tag{3}$$

According to Mellor, the maximum chipping depth should be less than the actual cutter working length; otherwise, the saw will be trying to cut more than is theoretically possible and the chain would bind. In this respect our saw seems to be correct. However, it is also desirable to cut as deeply as possible to produce cuttings as coarse chips rather than as shavings. This will facilitate the conveyance of cuttings and improve saw efficiency. If we file our gauge completely off to give a cutter working length of 0.2188 in. (7/32 in.), the theoretical maximum saw traverse speed that would be possible, accepting for the moment only the chipping depth constraint, is found by rearranging eq 2

$$U_{max}=(0.2188\times 2800)/2.25 \tag{4}$$

or $$U_{max}=272.3 \text{ ft/min} \tag{5}$$

We now need to look at cutting conveyance and how it affects cutting rate with our planned

modification. The space between teeth is used to convey cuttings to the surface, and the volume of cuttings produced per unit width of bar v_c is dependent upon cutting depth d, tooth spacing S, traverse speed U and tool speed u_t by the following equation

$$v_c = K_b S d(U/u_t) \tag{6}$$

where K_b is a bulking factor Mellor introduces to estimate the actual cutting volume from the in-place volume. He uses K_b=1.85 for rock, ice and similar materials.

The volume of cuttings produced must be carried away by the space between the teeth on the belt, which is calculated by

$$v_a = (S - s_t)h_t \tag{7}$$

where h_t is the height of the tooth above the belt and s_t is the effective tooth length defined as

$$s_t = v_t / h_t \tag{8}$$

where v_t is the tooth volume. In our saw h_t is approximately 0.125 in., s_t is approx 0.3125 in. and S is 2.25 in.

The space available for cuttings must be greater than or equal to the volume of cuttings produced

$$v_a \geq v_c \tag{9}$$

or

$$[1-(s_t/S)](h_t/d) \geq K_b(U/u_t)\ . \tag{10}$$

In our 7-in.-thick ice case this gives

$$(1-0.1389) \times (0.125/7) \geq 1.85(39.5/2800) \tag{11}$$

$$0.8611 \times 0.0179 \geq 1.85 \times 0.0141 \tag{12}$$

$$0.0154 \geq 0.0261 \tag{13}$$

where the values used for U were the average of all the 7-in. cut rates.

For the 11-in.-thick ice with U at 25.5 ft/min we get

$$0.0098 \geq 0.0168 \tag{14}$$

and finally for the 25-in. ice by using d=23 in. with U at 6.1 ft/min

$$0.0046 \geq 0.0040\ . \tag{15}$$

These computations are very theoretical and should be used as guidelines only, but nonetheless they indicate that cutting conveyance might not be adequate for the transverse rates achieved in the 7- and 11-in. ice and only marginally adequate in the 25-in. ice. We therefore might be able to improve our cutting rates by providing more chip removal capacity.

One relatively easy way to increase the volume available for cuttings is to increase the tooth spacing on the chain. Since the teeth on a chain saw are alternating pairs, we must be sure to preserve this pattern when we remove teeth. On the chains used in this study, that would result in a new spacing S of 6.625 in. Repeating the calculations above using this new value of S gives us the following. For 7-in. ice

$$0.0171 \geq 0.0261 \tag{16}$$

for 11-in. ice

$$0.0109 \geq 0.0168 \tag{17}$$

and for a 23-in. cutting depth

$$0.0051 \geq 0.0041\ . \tag{18}$$

It can be seen that increasing the spacing alone does not appear to be adequate for improving cutting rate. We could also decrease the height of the gauge, which would in effect increase the height of the tooth (h_t) to promote a deeper cut and more chipping. The maximum possible h_t with our chains is 0.2188 in., which would give the following. For 7-in. ice

$$0.0298 \geq 0.0261 \tag{19}$$

for 11-in. ice

$$0.0190 \geq 0.0168 \tag{20}$$

and for a 23-in. cutting depth

$$0.0091 \geq 0.0041\ . \tag{21}$$

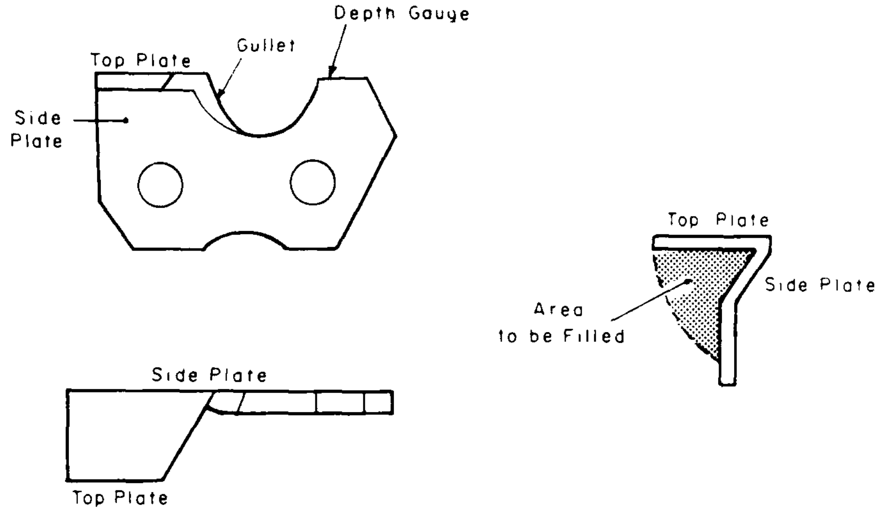


Figure 9. Chain saw cutter. Dashed line indicates area to fill in for improved cutting removal.

As can be seen this will be slightly better than the old configuration as far as the available space for cuttings, if we assume our old cutting rates. The fastest rates possible without violating the conveyance constraint are

$$U_{max}=[1-(s_t/S)(h_t/d)(u_t)]/K_b \tag{22}$$

for 7-in. ice

$$U_{max}=45.1 \text{ ft/min} \tag{23}$$

for 11-in. ice

$$U_{max}=28.8 \text{ ft/min} \tag{24}$$

and for a 23-in. cutting depth

$$U_{max}=13.8 \text{ ft/min} . \tag{25}$$

These rates would be 14, 13 and 126% improvements, respectively, over the actual average cutting rates obtained in the study.

A further modification that might improve shaving removal is to fill in the back area of the chain teeth between the side plate and top plate as shown in Figure 9. This could be accomplished with epoxy or solder and would offer a surface to carry more material out of the cut.

We also need to check the new configuration in regards to theoretical maximum chipping depth to ensure that we are not going over our actual chipping depth. The new maximum chipping depth, from eq 2, is

$$(45.1/2800) \times 6.625=0.67 \tag{26}$$

if we compute it at our theorized fastest average rate of 45.1 ft/min. This is less than the actual tooth length of 0.2188 and is therefore acceptable.

We obviously would want to improve our rate with the modification; so, to find the theoretical maximum cutting rate to which chipping depth will constrain us, we replace the maximum chipping depth in the above equation with our actual tooth length, which would be 0.2188 in. Solving for a new maximum cutting rate we find

$$(U_{max}/2800) \times 6.625 \leq 0.2188 \tag{27}$$

$$U_{max} = 92.5 \text{ ft/min.} \tag{28}$$

It is evident that chipping depth will not limit our cutting rate and it appears the above modifications could potentially give us a much higher rate.

CONCLUSIONS AND RECOMMENDATIONS

This study has shown us that a hand-held chain saw is an acceptable device to cut moder-

ate thicknesses of ice in a timely manner. The rate does go down considerably in 25 in. of ice, where it is only 15% of the 7-in. rate. A better method of cutting would be desirable in this situation if time is a factor.

The data in this study indicate that cutting rate is significantly affected by the chain type used and the ice thickness being cut. The operator seems to be less important as does the length of the cut. However, these conclusions need to be qualified.

The study tested only two operators and found that the difference between them was insignificant. To properly study the effect of a variable, we should choose that variable so that it represents the extreme ends of the spectrum of possible values. If that is done, then the effect that that variable might have is better delimited because a wider range of possible values has been included in the study. This study did not try to study the human operator over a wide range, e.g., by choosing a weak, inexperienced saw handler as one operator and a strong, experienced person as the other. If this had been done the operator variable might have shown more of an effect upon cutting rate.

The length of the cut also showed little effect upon the cutting rate but care should be taken to only apply this result between the 5- and 15-ft cut lengths. If a cut longer than 15 ft had been used, then perhaps cut length would play a stronger role in determining cut rate. This length was chosen as representative of the expected cuts to be made in a clearing operation, as explained before, and was therefore better suited for our needs.

Ice thickness was the only characteristic of the ice that was measured in this study. There could be factors within the ice, e.g., ice temperature, or grain size, that are in fact the dominant influence affecting cutting rate. Because of the way that this preliminary study was conducted, these factors would be "hidden" within the ice thickness variable. Further study should investigate the effect that these other conditions may have.

The simple act of filing 1/16 in. off the chain gauge can significantly increase the cutting rate. In this study the mean cutting rate of the modified skip-tooth chain was 81% higher than the unmodified skip-tooth chain in the 7-in. ice and 72% higher in the 11-in. ice, as shown in Table 9.

Further study will be undertaken to try out the proposed chain modifications to ascertain their effect upon cutting rate and to further refine the cutting rate prediction formula.

Table 9. Summary cutting rate statistics for the modified and unmodified chains in 7- and 11-in.-thick ice.

	Unmodified chain	*Modified chain*
7-in.-thick ice		
Sample size	12	12
Average	21.7783	39.49
Variance	4.057	125.659
Standard deviation	2.0142	11.2098
Standard error	0.581449	3.23598
Minimum	17.64	17.3
Maximum	24.32	50.0
Range	6.68	32.7
11-in.-thick ice		
Sample size	8	8
Average	14.8038	25.535
Variance	18.358	17.6078
Standard deviation	4.28462	4.19616
Standard error	1.51484	1.48357
Minimum	8.82	18.18
Maximum	19.99	31.57
Range	11.17	13.39

Information on the power requirements for cutting ice would be helpful in analyzing and designing better saw configurations. In this year's study, we planned to obtain power readings by instrumenting an electric chain saw. However, a recalcitrant portable generator won the first round and failed for all but a few readings. Next year will, we hope, see this corrected.

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